Kinematic and Electromyographic Analysis of Elbow Flexion During Inertial Exercise

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Inertial exercise protocols are currently used clinically to improve and restore normal muscle function even though research to substantiate their effectiveness cannot be cited in the literature. The purpose of this study was to compare simultaneous kinematic and electromyographic (EMG) data obtained from 12 subjects during elbow flexion on the Impulse Inertial Exercise System. Testing sessions consisted of inertial exercise performed using phasic and tonic techniques with loads of: a) 0 kg, b) 2.27 kg, c) 4.54 kg, d) 6.80 kg, and e) 9.07 kg. Greater peak angular velocities, peak platform accelerations (change in velocity of platform during elbow flexion), mean and peak triceps brachii muscle EMG activity, and less range of motion were observed during phasic exercise. There was also a general trend for peak angular velocities and peak platform acceleration to increase as the load decreased. No significant difference in mean or peak EMG activity of the biceps brachii muscle was seen between techniques. Clinicians and athletic trainers using inertial exercise should consider both the exercise technique and load characteristics when designing protocols to meet the specific needs of patients.

Inertial exercise is a relatively new and unique form of muscle loading[2] that simulates momentum and velocity changes occurring during functional activities. The Impulse Inertial Exercise System (EMA Inc, Newnan, GA) is an inertial exercise device that allows reciprocal acceleration and deceleration of a platform of variable mass along a horizontal track by a pulley cable system (see Figure).[1,9] Exercises can be performed in various functional or straight plane patterns to simulate the desired activity, all of which are controlled by the patient.[1,9]

Even though the clinical rationale for the use of inertial exercise is based on established physiological and mechanical principles, documentation pertaining to kinematic, kinetic, and electromyographic (EMG) measures during inertial exercise is yet to be reported. The literature substantiating the use of inertial exercise is therefore of a secondary nature and uses arguments not founded on research specific to inertial exercise. As a result, there is a need for the quantification of kinematic and EMG data specific to inertial exercise.

The purpose of this study was to biomechanically analyze and compare kinematic and EMG data collected during phasic and tonic elbow flexion inertial exercise with varied loads. Quantification of these variables in a controlled-exercise situation will provide objective data that can be related specifically to inertial exercise and its potential application in the functional training and rehabilitation of athletes and workers. We hypothesized that: 1) peak angular velocities, peak platform accelerations, and EMG activity of the biceps brachii and triceps brachii muscles during inertial exercise would be significantly different between loads; 2) peak angular velocities would exceed those currently attained with isokinetic devices; and 3) greater peak angular velocities, peak platform accelerations, and EMG activity would be attained with phasic exercise as compared to tonic exercise.

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METHODS

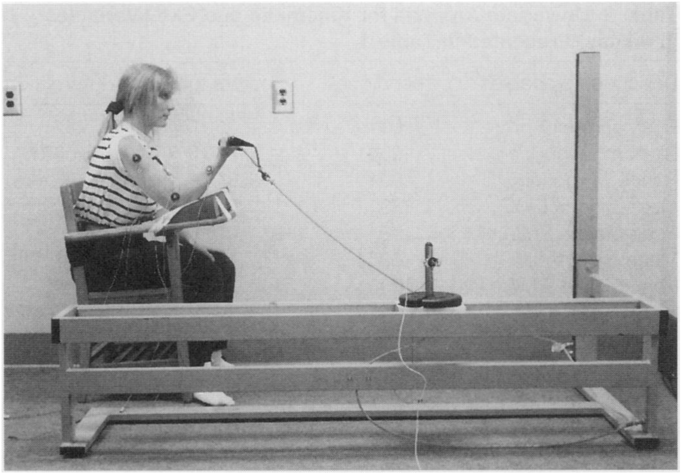
A 2 × 5 statistical design was used to guide this investigation. Independent variables were exercise technique (phasic and tonic) and load (0 kg, 2.27 kg, 4.54 kg, 6.80 kg, and 9.07 kg). Dependent variables were: 1) peak angular velocity, 2) peak platform acceleration, 3) range of motion, 4 & 5) mean and peak EMG activity of the biceps brachii muscle, and 6 & 7) mean and peak EMG activity of the triceps brachii muscle.

Twelve women (age = 22 ± 1.5 yr) volunteered to participate in this study. Subjects received an upper quarter clearing exam before testing to rule out any previous or current upper extremity dysfunction. We familiarized all subjects with the purpose of the study, testing procedure, and instrumentation, and had each sign an informed consent statement. The Georgia State University Institutional Review Board approved this study.

We collected simultaneous EMG and kinematic data from each subject during maximal effort elbow flexion on the Impulse Inertial Exercise System. We analyzed data extracted from one elbow flexion movement at each load during the testing sessions.

We obtained kinematic data from the WATSMART digital motion analysis system (Northern Digital Inc, Waterloo, Ontario, Canada), which has been shown to be reliable.[25] Sampling frequency was 200 Hz; angular velocity and acceleration data were calculated using differentiation of the marker position data. We used a 6-Hz Butterworth filter while collecting the acceleration data.

We collected EMG data with a Therapeutics Unlimited Model 544 Multichannel Electromyographic System (Thera-



Subject positioning and placement of IREDs during inertial exercise.

peutics Unlimited Inc, Iowa City, IA) using two 8-mm diameter silver/silver chloride electrodes (interelectrode distance of 22 mm) with an on-site solid-state amplifier embedded in a plastic enclosure. The signals were preamplified, transmitted, and amplified again such that a maximal signal was observed. The common mode rejection ratio is 87 dB at 60 Hz, and the input impedance is greater than 15 M ohms at 100 Hz. For ease of interpretation, we converted raw EMG signals to root mean square values at a time constant of 11.75 m/sec and converted to digital output via the WATSCOPE (Northern Digital Inc, Waterloo, Ontario, Canada) data acquisition system. We viewed the raw signals on a Tektronic storage oscilloscope (Tektronic Inc, Beaverton, OR) to allow observance of the converted signal for determination of proper amplitude settings.

We located the muscle bellies of the right biceps brachii and the lateral head of the right triceps brachii muscles during maximal voluntary isometric contraction of each muscle. We identified and marked the midpoint of each muscle belly with a permanent ink marker. We lightly abrased the marked area with sandpaper to decrease skin impedance, placed electrolyte cream on each electrode, and secured the electrodes over the abrased skin with prefabricated double-sided adhesive tape. Each testing session began with placement of the EMG electrodes. Gain settings as determined by pretesting were set at 1 K (K = 1000 times) for the biceps brachii and 2 K for the triceps brachii. We observed EMG activity on the oscilloscope during isometric muscle contraction of each muscle to verify proper signal amplitude.

We positioned and secured with double-sided adhesive tape, three infrared light-emitting diodes over each of three anatomical landmarks on the subject's right upper extremity (see Figure): a) 15.25 cm proximal to the elbow, b) over the lateral epicondyle, and c) 15.25 cm distal to the elbow. We also placed one infrared light-emitting diode on the sliding platform of the Impulse Inertial Exercise System to monitor the kinematics of the platform during testing. We used two cameras specifically designed to sense the infrared light emitted from the diodes during motion and integrated with the WATSMART system. The cameras were separated by a distance of 3 m, and positioned at a height of 2.5 m at a distance of 4 m from the Impulse Inertial Exercise System. The angle between the two cameras' central line of view as measured from their convergence point at the Impulse Inertial Exercise System's center was 29.

Before testing, we instructed each subject in the correct technique for phasic and tonic elbow flexion exercise and allowed time to practice each technique. When performing the phasic exercise, the subjects were instructed to move the platform as fast as they could, causing slack in the pulley cable. Pretesting showed that this task could be best accomplished if the subject performed the exercise through a limited range of motion. We instructed subjects to maintain constant tension on the pulley cable during exercise and to move the elbow through a larger range of motion than during phasic exercise. We seated subjects in a wooden chair with a backrest and secured their trunks with a waist belt. The elbow rested on a cushioned armrest to minimize shoulder activity (see Figure). Elbow and shoulder positioning before beginning testing were similar for all subjects. We did not position the shoulder or elbow in a standard position, based on the assumption that each subject would adapt to her optimum power production zone during the dynamic testing. Since peak kinematics of elbow flexion and extension were desired, positional postural requirements were less important than ensuring the subjects' attained maximal kinematic values.

We taped infrared-emitting diode markers to the anatomical landmarks described above. Testing consisted of one session of both phasic and tonic exercise separated by at least 1 day using randomly ordered loads of: 1) 0 kg, 2) 2.27 kg, 3) 4.54 kg, 4) 6.80 kg, and 5) 9.07 kg (plus weight of the sliding platform = 1.47 kg). Each session began with a 30-second warm-up with a 4.54-kg weight followed by a 3-minute rest. The subject then performed voluntary maximal effort elbow flexion/extension for 20 seconds at each load setting with a 3-minute rest interval between trials. During the exercise bout, we collected data during a 5-second interval when it was determined by the test administrator that the subject was performing the exercise according to the previously stated directions.

We obtained kinematic and EMG data on all 12 subjects during testing, and generated group means for the previously determined biomechanical variables. We extracted one complete cycle (flexion/extension) from the 5 seconds of data collected. This cycle reflected a dynamic state of maximal elbow flexion to extension and back to full flexion at each load setting, verified by analyzing the linear displacement of the platform during exercise.

We analyzed the data using a multivariate analysis of variance (MANOVA) for the effects of the factors, technique, load, and the technique by load interaction on all dependent variables. MANOVA significance using Wilks' criterion was determined at the $p < .05$ level. We further analyzed the data using univariate analysis to determine the effects of the factors on each dependent variable with significance being determined at the $p < .05$ level. We used Tukey's multiple comparison testing to further identify differences in means between different levels of the dependent variables in which there was univariate significance.

RESULTS

Means and standard deviations of the dependent variables obtained from tonic and phasic exercise techniques are shown in Table 1. The kinematic variable peak platform acceleration is seen to increase as the load decreases for both tonic and phasic exercise. During tonic exercise, peak angular velocity also increased as the load decreased. Phasic exercise did not show consistent findings except for increases in peak angular velocity from 0 kg to 4.54 kg. Mean and peak biceps brachii EMG activity increased as the load increased during tonic exercise but showed no consistent pattern during phasic exercise. Mean triceps brachii EMG activity deceased as the load increased during phasic exercise, as did peak triceps brachii activity except for a slight increase at 4.54 kg. EMG activity in the triceps brachii during tonic exercise showed minimal fluctuations.

There were overall significant differences between technique ($F(8,92) = 22.85$, $p < .0001$), load ($F(32,340) = 5.47$, $p < .0001$), and a technique by load interaction ($F(32,340) = 1.60$, $p = .0236$). The results of univariate analysis for each dependent variable for each of the factors are found in Table 2. Greater peak angular velocities and peak platform accelerations were seen with phasic exercise. Peak angular velocities were greater with 0 kg compared to all other loads and peak platform accelerations were significantly greater between loads of 0 kg, 2.27 kg, and 6.80 kg, but not between 6.80 and 9.07 kg. Range of motion was significantly greater in tonic versus phasic exercise. Mean and peak biceps brachii EMG muscle activity was not significantly different between exercise techniques but significantly greater mean and peak biceps brachii EMG activity was seen with a load of 9.07 kg versus 0 kg. The only significant difference reported for the mean and peak EMG activity of the triceps brachii was an increased activity during phasic exercise.

Table 2. Univariate Analysis for Kinematic and EMG Variables (p-values) Presented in Table 1

Dependent variables	Technique*	Factors load**	Interaction
Peak ang vel	.001	.0001	.87
Platform acc	.0001	.0001	.0001
Range of motion	.001	.81	.60
Mean biceps EMG	.39	.005	.30
Peak biceps EMG	.95	.007	.20
Mean triceps EMG	.0004	.74	.28
Peak triceps EMG	.0001	.71	.32

F values: F(1,99) technique, F(4,99) load, F(4,99) interaction.
Significance determined at $p < .05$.
* Tonic vs Phasic.
** Tonic & Phasic data combined.

DISCUSSION

The basic principles of inertial exercise can all be related to Newton's three laws of motion. The load placed on the sliding platform acts as the mass, while force corresponds to muscular forces which initiate and accelerate a mass through a pulley cable system.[1,14] The momentum and acceleration/deceleration forces change as the velocity and direction of motion of the sliding platform are altered.[1] By definition, inertia refers to the resistance an object offers to a change in its momentum,[14] while moment of inertia refers to the resistance of a lever arm to a change in angular motion. Impulse refers to summation of forces associated with the accelerations and decelerations during exercise that are absorbed by the muscle during a specified period of time.[1,12,14]

Physiologically, inertial exercise is a form of plyometric exercise based on the principles of the stretch-shorten cycle.[1,4,8,11,21] When performed properly, inertial exercise enhances the power generated in the muscle by using stored elastic energy in the series elastic component of the muscle and

Table 1. Dependent Variables Measures for Tonic and Phasic Exercise Techniques (mean ± SD)

Load		0 kg	2.27 kg	4.54 kg	6.80 kg	9.07 kg	Statistics*
Peak ang vel (°s^{-1})	tonic	392 ± 108^{b}	348 ± 85^{a,b}	320 ± 84^{a}	284 ± 57^{a}	278 ± 94^{a}	T, L
	phasic	490 ± 177	421 ± 126	356 ± 122	379 ± 137	356 ± 164	T, L
Peak platform acc (°s^{-2} × 10^{3})	tonic	27.2 ± 8.3^{a}	22.1 ± 7.9^{b}	16.7 ± 6.1^{c}	16.9 ± 7.0^{c,d}	14.5 ± 3.2^{d}	T, L, I
	phasic	45.7 ± 13.1	35.2 ± 7.2	23.9 ± 5.9	20.1 ± 3.9	16.5 ± 3.1	T, L, I
Range of motion (°)	tonic	49 ± 13	54 ± 19	51 ± 16	49 ± 16	50 ± 18	T
	phasic	43 ± 8	41 ± 11	36 ± 12	43 ± 12	38 ± 12	T
Mean biceps EMG (mV)	tonic	.87 ± .36^{b}	1.05 ± .47^{a,b}	1.25 ± .64^{a,b}	1.43 ± .58^{a,b}	1.5 ± .68^{a}	L
	phasic	1.19 ± .55	1.11 ± .55	1.47 ± .67	1.35 ± .62	1.33 ± .77	L
Peak biceps EMG (mV)	tonic	3.43 ± 1.25^{b}	3.83 ± 1.8^{b}	4.68 ± 2.67^{a}	5.08 ± 1.98^{a,b}	5.34 ± 2.54^{a,b}	L
	phasic	4.15 ± .8	3.83 ± 1.96	5.44 ± 2.43	4.44 ± 1.9	4.41 ± 2.21	L
Mean triceps EMG (mV)	tonic	.31 ± .31	.31 ± .25	.34 ± .33	.33 ± .27	.33 ± .34	T
	phasic	.57 ± .29	.49 ± .22	.44 ± .24	.41 ± .15	.39 ± .22	T
Peak triceps EMG (mV)	tonic	.94 ± .80	.99 ± .92	.99 ± .93	1.01 ± .83	1.12 ± 1.27	T
	phasic	2.26 ± 1.15	1.99 ± .96	2.08 ± 1.7	1.7 ± 1.01	1.52 ± 1.1	T

* Statistical difference between means $p < .05$ (see Table 2).
T = Technique significantly different.
L = Load significantly different.
I = Technique × Load interaction significantly different.
Loads with same letter are not significantly different.

by excitation of muscle spindles during the quick muscle stretch (myotatic reflex) experienced at the end of the deceleration or eccentric phase.[1,4,5,7,13] The enhancement of these neurological and viscoelastic properties can be used to generate acceleration for the next concentric muscular contraction.[1,19] The ability to use the elastic and neurophysiological properties of muscle is theorized to facilitate increased muscle recruitment in a minimal amount of time and is interpreted clinically as increased power.[1,4] Komi et al[13] showed that stored elastic energy in the muscle was recovered most effectively when the amortization phase (the amount of time between a muscle's transition from an eccentric contraction to the initiation of a concentric contraction) was short. The ability to use this elastic energy in the muscle is also affected by time, magnitude of stretch, and velocity of stretch, all of which can be controlled during inertial exercise by changing either the load or exercise technique.[4,13]

Albert[1] described two specific inertial exercise techniques: phasic and tonic. The phasic exercise technique is characterized by cyclic bursts of muscular co-contraction, which allows slack in the pulley cable during contraction and would theoretically constitute more muscle spindle feedback and function to recruit dynamic joint stability. The tonic exercise technique is characterized by muscle contractions, which maintain a constant tension in the pulley cable throughout the exercise, emphasizing optimal joint stability.

Albert also studied the influence of inertial exercise on muscle torque in the biceps brachii. A pilot study done in 1987[1] found no significant increase in concentric isokinetic peak torque at 90°/sec or 300°/sec in subjects who trained on the Impulse Inertial Exercise System three times a week for 5 weeks. Albert postulated that the lack of increases was because angular velocities during training sessions exceeded the velocities used during isokinetic testing. In a second study, Albert[2] found increased concentric and eccentric torque at 60°/sec and eccentric torque at 120°/sec after a 5-week inertial exercise training program.

The results of our study support the hypothesis that significantly greater peak angular velocity, peak platform acceleration, and mean and peak EMG activity in the triceps brachii muscle occur with phasic exercise. Our hypothesis that greater range of motion occurs with tonic exercise was also supported, as was the hypothesis that peak angular velocities and peak platform accelerations would be different for the different loads with a general trend for these variables to increase as the load decreased. The increases in angular velocity and platform accelerations as load decreased is consistent with the typical force velocity curve.[14] The findings of this study did not support the hypothesis of increased mean or peak EMG activity in the biceps brachii muscle during phasic exercise.

Maximum peak angular velocity averaged 490°/sec with a standard deviation of 177°/sec during phasic exercise with a 0-kg load. These values indicate that velocity values greater than 600°/sec are attainable in some subjects and support Albert's clinical hypothesis[1] that exercise on the Impulse Inertial Exercise System is capable of exceeding velocities associated with most isokinetic devices. These peak elbow angular velocities are, however, still considerably lower than those reported in baseball pitchers, 2200°/sec[23] and 4595°/sec,[20] and in water polo players, 1200°/sec.[23]

The significantly greater peak angular velocities and peak platform accelerations during phasic exercise suggest the clinical use of this technique, particularly in patients or athletes involved in dynamic activities.[1,16,21] The large accelerations observed during phasic exercise are likely to cause more stretch on the series elastic component and greater muscle spindle feedback. The long-term effect of this type of high dynamic training may be increased dynamic stabilization of the joint.[1] In contrast, tonic exercise resulted in significantly lower peak angular velocities and peak platform accelerations through a larger range of motion, which may indicate that this type of exercise is better suited for training programs designed for joint stability.[1]

The EMG activity during inertial exercise was significantly greater in the triceps brachii muscle during phasic exercise. No significant differences were observed in the EMG activity of the biceps brachii muscle between the two exercise techniques, although significantly more biceps brachii activity was seen for exercise using a load of 9.07 kg, versus 0 kg. Triceps brachii muscle EMG activity showed a consistent decrease in EMG activity as load increased during both tonic and phasic exercise, while the biceps brachii muscle showed a general increase in EMG activity during tonic exercise as the load increased and no trend in EMG activity as the load increased during phasic exercise.

One possible explanation for the EMG activity observed in this study could be related to the orderly recruitment of motor units in human muscle from the smaller slow twitch to the larger fast-twitch fibers as the demands for more forceful powerful actions are required.[6] This seems to be true for the biceps brachii muscle, which, in this study, is the prime mover responsible for initiating movement along the horizontal track. During tonic exercise, the biceps brachii muscle generally showed increased activity as mass increased, indicating more motor unit recruitment as the load increased.[6] This relationship was probably not observed in the phasic exercise because larger bursts of muscle activity may recruit all muscle types. The more powerful ballistic nature of this exercise was likely to cause more synchronous activation of all available motor units, violating the normal recruitment sequence.[10] The limited activity in the triceps brachii muscle during tonic exercise is likely related to the slower nature of this exercise and the fact that the triceps brachii muscle did not have to overcome a substantial amount of resistance during extension of the elbow. During phasic exercise, the triceps brachii muscle was required to move more quickly in a more ballistic manner, which may account for the greater EMG seen with phasic exercise.[10]

Clinically, we know that many shoulder injuries are a result of the deceleration forces imparted to the shoulder tissues during the follow-through phase of throwing, while most elbow injuries are attributed to forces created during the acceleration phase.[18,20] High-velocity joint rotations, combined with factors such as muscle imbalances, inadequate coordination of the muscles surrounding a joint, decreased flexibility, or fatigue can alter the body's ability to properly absorb the acceleration and deceleration forces directed into the joint area.[3,18]

Inertial exercise, because it more closely simulates the normal acceleration/deceleration forces created around a joint during functional and sport-specific activities,[17,22] may prove a more useful training tool to prevent injury than currently used protocols. Training of the neural component of the neuromuscular system attained through the practice of specific skills appears to be as important as muscle strength in perfecting certain skills and preventing injury.[18,24] Inertial exercise, therefore, offers advantages over current isokinetic devices which are limited by: 1) a fixed plane of motion, 2) a lack of specific functional or closed chain testing modes, 3) maximal velocities up to 600°/sec, and 4) constant velocity settings with minimal acceleration and deceleration.[1] As a result, inertial exercise more realistically replicates the true kinematics and kinetics present in most sport- or work-related activities that involve significant joint accelerations and decelerations.[1]

More research is needed to fully understand the potential and application of inertial exercise in rehabilitation and in specific sports training programs. Specific factors, such as changes in the length of the amortization phase as described by Komi et al,[13] need to be quantified at different load settings and before and after training. More detailed EMG analysis related to specific timing of EMG activity relative to the position of the moving platform and to the stretch-shorten cycle needs to be examined. This type of information would add credibility to, or refute the many untested theories associated with inertial exercise and EMG activity. Specific points such as the catch phase described by Albert[1] also need to be quantified to actually describe the biomechanical factors at play when significant changes in joint velocity occur during inertial exercise. The implications for work and sport-specific training programs need further investigation, especially as to the possible improvement in these tasks as documented by improved performance. The use of inertial exercise as a training device in which subjects are given ample time to perfect the exercise skill may also result in even greater angular velocity values.[15]

CONCLUSION

The data collected in this study provide objective kinematic and EMG data for elbow flexion motion during inertial exercise performed at five different loads. 1) There were significant differences between the phasic and tonic exercise technique and between different loads. 2) There was a general trend for peak angular velocity and peak platform accelerations to increase as the load decreased. 3) There was significantly greater mean and peak triceps brachii muscle activity (EMG) during the phasic exercise and significantly greater mean and peak EMG activity in the biceps brachii muscle between the loads of 9.07 kg and 0 kg. 4) Significantly greater range of motion occurred during the tonic exercise. 5) Athletic trainers using inertial exercise should therefore consider both the exercise technique and load parameters when designing protocols to meet the specific demands of their patients and athletes.

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